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# MULTI-OBJECTIVE METHODS FOR DETERMINING OPTIMAL VENTILATION RATES IN DWELLINGS

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## ABSTRACT

The optimal ventilation rate in a dwelling is a trade-off between the requirement to minimize ventilation heat losses to help meet national greenhouse gas emission targets and the need to minimize adverse health impacts arising from exposure to cold temperatures and pollutants from indoor and outdoor origin. This paper presents two multi-objective optimization methods for exploring these trade-offs. The first method relies on monetization of the various performance criteria, while the second method weights them in a more general way.

The generalized multi-objective optimization approach is found to be robust against any scaling in the health impacts and energy savings, and therefore is less dependent on assumptions made in the models such as heating system efficiency, toxicity of pollutants, and dwelling occupancy, unlike in the monetization approach. It is however sensitive to assumptions that affect health impacts and energy savings in a way that is correlated with ventilation rate, such as pollutant production rates, or balance-point temperatures.

A preliminary application of the methods to a typical UK flat and detached house finds that the optimal ventilation rate may vary according to the built form, with a far greater value in

the flat compared to the detached house. Both the monetization approach and generalized multi-objective optimization approach, in which health impacts and energy savings are equally weighted, suggest an optimal annual average air change rate of 0.4/hr for the detached house, and 0.8/hr for the flat. This is equivalent to ventilation rates of 0.3 l/s/m$^2$ for the detached house and 0.5 l/s/m$^2$ for the flat.


## KEYWORDS

**Ventilation rate, multi-objective optimization, indoor air quality; health impacts; space heating demand**


## ABBREVIATIONS

| | |
|---|---|
| $PM_{2.5}$ | Particulate matter found in the air with a diameter of less than 2.5 μm. |
| ETS | Environmental Tobacco Smoke. |
| $ACH_{yr}$ | Annual average air change rate of the conditioned zones of a dwelling (/hr). |
| $C_{iPM,yr}$ | Annual average concentration of $PM_{2.5}$ from internal sources assuming a 0.45:0.45:0.10 occupancy weighting between the bedroom, living room, and the kitchen (μg/m$^3$). |
| $C_{ePM,yr}$ | Annual average concentration of $PM_{2.5}$ from external sources assuming a 0.45:0.45:0.10 occupancy weighting between the bedroom, living room, and the kitchen (μg/m$^3$). |
| $C_{I/O,yr}$ | Annual average concentration of $PM_{2.5}$ from external sources indoors as a ratio of the external concentration of $PM_{2.5}$, assuming a 0.45:0.45:0.10 occupancy weighting between the bedroom, living room, and the kitchen. |
| $C_{rad,yr}$ | Annual average concentration of radon assuming a 0.45:0.45:0.10 occupancy weighting between the bedroom, living room, and the kitchen (Bq/m$^3$). |
| $C_{ETS,yr}$ | Annual average concentration of ETS assuming a 0.45:0.45:0.10 occupancy weighting between the bedroom, living room, and the kitchen (μg/m$^3$). |
| $SIT_5$ | Standardized Internal Temperature in the living room at an external |

| | |
|---|---|
| | temperature of 5˚C (°C). |
| $MSI_{\%>1}$ | Percentage of a population of dwellings with a Mould Severity Index greater than 1 (%). |
| $iPM_{2.5}$ CP | Cardiopulmonary mortality due to exposure to internal sources of $PM_{2.5.}$ |
| $ePM_{2.5}$ CP | Cardiopulmonary mortality due to exposure to external sources of $PM_{2.5.}$ |
| $iPM_{2.5}$ LC | Lung cancer mortality due to exposure to internal sources of $PM_{2.5.}$ |
| $ePM_{2.5}$ LC | Lung cancer mortality due to exposure to external sources of $PM_{2.5.}$ |
| Radon LC | Lung cancer mortality due to exposure to radon. |
| ETS CA | Cerebrovascular accident (stroke) mortality due to exposure to ETS. |
| ETS MI | Myocardial infarction (heart attack) mortality due to exposure to ETS. |
| Cold CV | Cardiovascular mortality due to exposure to cold temperatures in winter. |
| $t_e$ | External temperature (°C). |
| $t_{bal}$ | Balance-point temperature (°C). |
| $H(\tau)$ | Heat-loss coefficient at time $\tau$ (W/K). |
| $\dot{q}$ | Rate of energy consumption for space heating (W). |
| $q_{yr}$ | Annual space heating demand (kWh). |
| $\eta$ | Heating system efficiency (%). |
| $ACH_{yr,yref}$ | A reference annual average air change rate of 0.5/hr (/hr). |
| QALY | Quality-Adjusted Life Year. |

# 1 INTRODUCTION

National greenhouse gas reduction commitments make it necessary to reduce dwelling heat losses via ventilation by reducing the permeability of dwellings that comprise the UK housing stock. It is estimated that ~20% of an average UK dwelling's heating load is accounted for by the infiltration of cold air [1] . However, people in the UK spend over 70% of time in their homes [2]. Therefore, a possible unintended consequence of energy efficiency measures is a corresponding increase in personal exposure to pollutants such as mould, radon, and particulate matter (PM) [3]. It is thought that this increased exposure could significantly affect overall population health [4].

Radon, for example, is responsible for 1100 (3.3% of all) annual lung cancer deaths [5] caused by the inhalation and bronchial deposit of radon progeny [6]. High levels of moisture lead to problems with mould growth and consequent emissions of spores and volatile organic compounds [7,8] The combined effects of dampness are linked to negative respiratory symptoms and asthma. The smaller fractions (diameter of <2.5μm) of particulate matter (PM) are particularly harmful to health [9] and originate from both internal and external sources. Internally, dominant sources include cooking and tobacco smoking [10]. Environmental tobacco smoke (ETS) is an aerosol comprised of thousands of substances distributed as particles, vapours, and gases and is important because firstly, a substantial proportion of the population is regularly exposed to it and secondly, the act of tobacco smoking can temporarily raise local internal $PM_{2.5}$ concentrations up to 1000 $\mu g/m^3$ [6]. There are also health benefits such as improved indoor temperatures [e.g. 11], and a lower exposure to outdoor pollutants.

The ideal ventilation rate is therefore a compromise between the need to reduce heat loss through ventilation, maintain thermal comfort, reduce ingress of outdoor pollutants, and ensure the removal of indoor pollutants. Approved Document Part F (ADF) of the UK Building Regulations [12] requires a minimum whole dwelling ventilation rate of not less than 0.3 l/s per square metre of internal floor area. For many UK dwellings this corresponds to a minimum whole dwelling air change rate per hour of approximately 0.5/hr, a minimum rate set by many European countries for dwellings, and reported as a threshold rate above which some negative health effects reduce [13,14]. There is an obvious need to explore the ideal ventilation rate in more detail by explicitly considering several contributing factors.

Multi-objective optimization offers an approach for exploring optimal values of a variable when several and often competing objective functions (e.g. ventilation heat losses, negative health impacts) exist. There are two general approaches to multi-objective optimization. One is to combine the individual objective functions into a single objective function by for example an appropriate weighting scheme, or by converting all but one objective function into constraints [15]. In both cases, an optimization method would return a single solution for each choice of weights or constraints, but these weights and constraints could be varied in order to obtain a set of solutions to help decision-makers examine trade-offs. The second general approach is to determine the entire set or a representative set of 'Pareto optimal solutions', in which the least value of each objective function is obtained within acceptable levels, without dominating other objective functions. While moving from one Pareto solution to another, there is some sacrifice in one objective function(s) to achieve a gain in the other(s), therefore easily allowing the decision-maker to examine trade-offs.

Multi-objective optimization methods are used widely in several research fields as an approach for optimizing a whole range of design problems, for example in determining the optimal aerodynamic shape [16], designing ovens for optimizing commercial bread-making [17], operating reservoirs [18], and the design and implementation of renewable energy technologies [e.g. 19,20]. Such methods have also been applied to the improvement of the building performance of residential dwellings. [21] and [22] look at the optimal retrofitting of residential dwellings such that energy consumption, environmental impacts, and financial costs are all minimized. [23] and [24] additionally consider thermal comfort in the optimization of retrofitting measures.

This paper presents approaches for exploring ideal ventilation rates in residential dwellings using multi-objective optimization methods that consider energy efficiency as well as health impacts arising from indoor temperatures and exposure to a range of indoor pollutants. The multi-objective optimization approaches are illustrated with typical naturally-ventilated flats and detached houses, enabling an initial insight into how recommended ventilation rates may vary in dwellings when several contributing factors are taken into account.

The multi-objective optimization approaches and models of the indoor environmental quality, associated health impacts, and potential energy savings are described in Section 2. The results are presented in Section 3. Interpretation of the results and inherent uncertainties in the application of the proposed methods to the case-study dwellings are discussed in Section 4. Finally, the conclusions and possible future avenues of research are described in Section 5.

# 2 MATERIALS AND METHODS

Two implementations of the weighted-sum multi-objective optimization approach are applied here to explore optimal ventilation rates and the resulting trade-offs between indoor environmental quality and energy savings. The methods are applied to a naturally-ventilated flat and house, also modelled in [4,25,26]. Modelled indicators of the indoor environmental include concentrations of $PM_{2.5}$, radon, ETS, indoor temperature in the winter months, and the risk of mould growth during the winter months. The various indicators are compared on an equal footing by investigating their impact on health compared to reference dwellings. The energy savings for each of the modelled dwellings compared to the reference dwellings are also evaluated.

## 2.1 OPTIMIZING VENTILATION RATES WITH RESPECT TO MULTIPLE CRITERIA

Let us assume that there are several performance criteria that vary with the annual average air change rate in a dwelling ($ACH_{yr}$) from which a single optimum value is to be derived. For clarity, let us denote $ACH_{yr}$ by $x$ and denote the different performance criteria by $f_1(x), f_2(x), \ldots f_n(x)$ where $n$ is the total number of performance criteria or objective functions. In a multi-objective optimization framework, some of the criteria are to be maximized whilst others are to be minimized. Without loss of generality, we can assume that all the criteria are to be minimized because $f_i$ can always be replaced by $-f_i$.

Here we explore two versions of the weighted-sum method to find the optimal value for $x$ with respect to two performance criteria; annual health impacts and annual energy savings due to changes in ventilation heat losses. The first approach monetizes each performance criterion and then aggregates the monetized criteria to create a single performance criterion, and the second takes a more generalized approach.

### 2.1.1 *MONETIZATION APPROACH*

In this approach the performance criteria are combined to calculate a single performance measure or objective function by first converting each to a monetary value:

$$F(x) = \sum_{i=1}^{n} c_i \times f_i(x) \tag{1}$$

where $\{c_i; 1 = 1..n\}$ are the costs assigned to each criterion. In the evaluation of health technologies, the National Institute of Clinical Excellence (NICE) generally considers a treatment to be not cost-effective (relative to a comparator) if it costs more than £20,000-£30,000 per Quality-Adjusted Life Year [27], or QALY. Therefore in this work we monetize annual health impacts assuming a range between £20,000-£40,000 per QALY to account for inflation during the 10 years since this study. Positive costs correspond to money saved and therefore the health impacts term is given a negative sign.

Domestic electricity and gas cost a minimum of 5p/kWh and 2.7p/kWh respectively in 2012 [28]. Assuming total energy consumption in kWh is divided in a 1:5 ratio[1] between electricity and gas, this gives a minimum domestic energy price of 3.3p. Therefore we monetize annual energy savings assuming a price in real terms between 3p/kWh and 10p/kWh, a possible future price on the extreme end of the scale. If a minimum point exists (i.e. if $F(x)$ is convex),

[1] http://www.ofgem.gov.uk/Markets/RetMkts/Compl/Consumption/Pages/ConsumptionReview.aspx

the function is minimized numerically to determine the optimal $x$. Otherwise, the optimal $x$ is that corresponding to the minimum $F(x)$ over the range of modelled $x$.

### *2.1.2 Generalized multi-objective optimization approach*

In this approach each criterion is first normalized to get all the criteria on equal footing. Let us denote by $\bar{f_i}$ an 'appropriate' upper bound of $f_i(x)$ and define the transformed criterion as:

$$g_i(x) = \frac{f_i(x)}{\bar{f_i}} \quad (2)$$

Now define a single objective function as the weighted sum of the single objective functions:

$$G(x) = \sum_{i=1}^{n} w_i \times g_i(x) \quad (3)$$

where $\{w_i; 1 = 1..n\}$ are the relative weights $0 \le w_i \le 1$ such that $\sum_{i=1}^{n} w_i = 1$. The choices of the relative weights can be elicited from experts but in this work the whole range between 0 and 1 for each weight is explored. Again, if $G(x)$ is convex, a numerical minimization technique is used to determine the optimal $x$. Otherwise, the optimal $x$ is that corresponding to the minimum $G(x)$ over the range of modelled $x$.

## 2.2 Models of indoor environmental quality

The validated multizone ventilation and pollutant transport model, CONTAM [29], is used to model indoor levels of $PM_{2.5}$ from internal and external sources, radon, ETS, and moisture. Indoor temperatures and risk of mould growth are estimated using empirical relations determined in the Warm Front Study [11,30,31]. The case-study dwellings and CONTAM models are already described in previous work and therefore reiterated only briefly below.

### *2.2.1 Construction of CONTAM models*

The flat consists of a living room, a kitchen, a bathroom, a store, and a landing, and has two exposed façades only. The detached house has an underfloor area (assumed to be unconditioned), a ground floor, a first floor, and a loft (also assumed to be unconditioned). The ground floor has a kitchen, a living room, a toilet, and a landing. The first floor has three bedrooms, an en-suite bathroom attached to the master bedroom, a second bathroom, and a landing connected to that on the ground floor by a staircase.

Air exchange between the dwellings and their external environment is assumed to occur via permeable exposed façades and via the opening of windows. Neighbouring flats are assumed to have the same indoor conditions as the modelled flat and hence there is no airflow at the inter-flat boundaries during operating conditions. Air exchange between indoor zones is possible through doors, which are closed when the zones are occupied, but open otherwise. In the house there is also airflow through floors. No trickle ventilator, extract fan, or mechanical ventilation components are modelled, as the primary intention of this work is to illustrate the application of a novel methodology to simple, but contrasting and realistic case-studies.

Winter and summer weather files constructed by [26] for London from the CIBSE[2] Test Reference Year (TRY) and Design Summer Year (DSY) data sets are used to describe external conditions. Weekly indoor temperature profiles are used from a study by [32]. They differ between summer and winter, but are the same in each zone, therefore possibly leading to an underestimation of buoyancy driven flows between zones.

Outdoor wind pressure coefficients are applied to the ventilation components allowing exchange with the external environment according to the profile of [33], and indoor wind pressure coefficients are assumed to have negligible contribution due to zero air movement indoors.

Six ‘contaminants’ are specified in the models. Dry air and water are assumed to be non-trace (i.e. they affect the density of the air). The four remaining contaminants are internal $PM_{2.5}$, external $PM_{2.5}$, radon, and ETS, all assumed to be trace contaminants. The moisture content indoors is due to moisture ingress from the external environment specified in the weather files, and due to moisture production by showers, cooking, and occupants. The ratio of the concentration of water to that of dry air gives the humidity ratio, which is important for calculations of mould risk. ETS is modelled assuming one smoker, and internal and external $PM_{2.5}$ sources are modelled separately to enable the ratio of the external $PM_{2.5}$ indoors as a ratio of the outdoor concentration of $PM_{2.5}$ (I/O) to be determined. Internal $PM_{2.5}$ ($iPM_{2.5}$) is assumed to be produced by cooking only and external $PM_{2.5}$ ($ePM_{2.5}$) is assumed to have a constant concentration of 13µg/m$^3$. Radon is assumed to seep in from the ground at a constant rate.

### *2.2.3 CONTAM RUN SPECIFICATIONS AND OUTPUTS*

The models are run for a whole year and for permeabilities ranging between 3 and 50 m$^{3/}$m$^2$/hr@50Pa are modelled, going beyond those measured for the UK housing stock [34] (between 3 and 30 m$^{3/}$m$^2$/hr@50Pa) to enable a large range of ventilation rates to be

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investigated. In reality, this additional ventilation rate could be provided by a trickle vent or mechanical ventilation system.

The total $ACH_{yr}$ of the conditioned zones in the building envelope is calculated from the hourly outputs of CONTAM. It should be noted that the use of this annual average masks the effectiveness of the removal of cooking-related pollutants and moisture at the source via purge ventilation through window opening. It is associated with lower values of $PM_{2.5}$ and mould risk than a dwelling with the same $ACH_{yr}$ achieved by a constant ventilation rate throughout the year.

All pollutant concentrations, except for humidity ratios, are averaged in each zone for the year of the simulation and then weighted in each dwelling assuming that 45% of an occupant's time is spent in the bedroom, 45% is spent in the living room, and the remaining 10% is spent in the kitchen. Radon concentrations are further scaled assuming 90% of the stock has radon emission rates of 0.005 $Bq/m^2$, 9% have radon emission rates of 0.05 $Bq/m^2$, and 1% have emission rates of 0.01 $Bq/m^2$ to fit the distribution of radon concentrations determined by [5]. For flat archetypes, an adjustment is made assuming 40% of flats are on the ground floor with the full 0.9:0.09:0.01 concentration, 14% of flats are on the 1$^{st}$ floor with half of the 0.9:0.09:0.01 concentration, and the remaining flats have zero concentration. ETS is further scaled by the stock average for ETS, calculated assuming the permeability distribution from [34] and archetype distribution (17% flats and 83% houses) found in the English Housing Survey [35].

Final outputs of indoor pollutant concentrations in the zones are aggregated in the ratios 0.45:0.45:0.10 (assuming 45% of an occupant's time is spent in the living room, 45% in the bedroom, and 10% in the kitchen) and then averaged over the year to give annual average concentrations $C_{\mathrm{iPM,yr}}$ ($\mu g/m^3$), $C_{\mathrm{ePM,yr}}$ ($\mu g/m^3$) scaled $C_{\mathrm{ETS,yr}}$ (dimensionless), weighted $C_{\mathrm{rad,yr}}$ ($Bq/m^3$), and $C_{\mathrm{ePM,yr}}$ ($\mu g/m^3$), which is also calculated as a ratio of the external concentration of $PM_{2.5}$ to give the annual average indoor/outdoor ratio of external $PM_{2.5}$, $C_{\mathrm{I/O,yr}}$.

### *2.2.4 Indoor temperature and mould risk from the Warm Front Study*

The Standardized Internal Temperature at an external temperature of 5°C in the living room ($SIT_5$) is used as a proxy for indoor temperatures and for the estimation of the risk of mould. $SIT_5$ is estimated from the modelled permeability, using empirical relations found in the Warm Front Study [11,31]. For permeabilities above measured values, a simple linear extrapolation is used. The proportion of a population of each archetype and permeability combination with a Mould Severity Index > 1 ($MSI_{\%>1}$) is estimated using an empirical relation determined in the Warm Front Study [30], the estimated $SIT_5$, and the modelled indoor humidity ratios.

## 2.3 Health impacts resulting from indoor environmental quality compared to reference dwellings

A health impacts model is used to estimate changes in mortality and morbidity due to changes in indoor exposure to ETS, both internally and externally-generated $PM_{2.5}$, cold (as a result of temperatures in the living room during winter), and mould (in the living room during winter) compared to reference dwellings. Several possible health outcomes are considered and summarized in Table 1 and Table 2. Toxicities of indoor and outdoor $PM_{2.5}$ are assumed to be the same, though the relative risks associated with outdoor $PM_{2.5}$ are far more clearly established. The health impacts model calculates changes in mortality rates for an individual in England and Wales at each year of age, using a standard life table methodology [36]. Mortality rates are adjusted in response to the change in exposures compared to a reference dwelling. The final output is a population-weighted average change in QALYs per year, calculated separately for males and females. The change in QALYs for males and females are then averaged to give the change in QALYs per individual per year. An increase in QALYs signifies a positive health impact.

**Table 1: Mortality outcomes modelled and exposure-response relationships**

| Exposure | Health outcome | Exposure-response function | |
|---|---|---|---|
| | | **Relative Risk** | **Reference** |
| $SIT_5$ | Winter excess cardiovascular mortality | 0.98 per °C standardised indoor temperature | Warm Front Study (unpublished) |
| ETS | Cerebrovascular accident mortality | 1.25 (if in same dwelling as smoker) | [37] |
| | Myocardial infarction mortality | 1.30 (if in same dwelling as smoker) | [38] |
| $iPM_{2.5}$ and $ePM_{2.5}$ | Cardiopulmonary mortality | 1.082 per 10 μg/m$^3$ | [39,40] |
| | Lung cancer mortality | 1.059 per 10 μg/m$^3$ | [39,40] |
| Radon | Lung cancer mortality | 1.16 per 100 Bq/m$^3$ | [41] |

Changes in respiratory morbidity are weighted to account for the reduced quality-of-life experienced; using weightings estimated from the literature [e.g. 42] (see Table 2). The quality weightings act as a downward scaling from perfect health. As such, a higher weighting represents a better quality of life (a quality weighting of 1 would represent perfect health, while a weighting of 0 would in theory represent death). The final outputs are changes in QALYs per dwelling per year. Again, an increase in QALYs signifies a positive health impact. As the mortality outputs are per individual and morbidity outputs are per dwelling, the mortality outputs are first multiplied assuming an average UK dwelling occupancy of 2.4 before summing with the change in QALYs due to morbidity impacts to obtain the total health impacts in QALYs per dwelling per year.

**Table 2: Morbidity outcomes modelled, QALY weights and exposure-response relationships.**

| **Exposure** | **Health outcome** | **QALY weight** | **Exposure-response function** | |
|---|---|---|---|---|
| | | | **Relative Risk** | **Reference** |
| Mould | Respiratory illness: | | | |
| | Harm class II (hospital admission) | 0.75 | 1.53 | Based on [43] (and as used in the Housing Health & Safety Rating Scheme) |
| | Harm class III (GP consultation) | 0.9 | 1.53 | As above |
| | Harm class IV (minor symptoms) | 0.9 | 1.83 | As above |

The required inputs to the health impact models are changes in exposures relative to the exposures in a chosen reference dwelling. Exposures in flats and houses are compared to those in the same archetype with an annual average ACH of 0.5/hr (recommended by many European countries), denoted by $ACH_{yr,ref}$. Piecewise cubic-hermite interpolation is used to estimate each exposure at $ACH_{yr,ref}$ in the flat and house and the reference exposures are then subtracted from the exposures calculated in the CONTAM models in order to obtain the changes in exposures.

## 2.4 Energy savings compared to reference dwellings

The space heating demand due to ventilation heat losses is estimated using the degree-hour method [44], that counts degree-hours based on the balance-point temperature $t_{bal}$. This is defined as the external temperature $t_e$ at which the building does not require supplementary heating or cooling, and is assumed to be 15.5°C here [45]. In the heating season, the internal heat gains provide sufficient heating down to the balance-point temperature. Below that temperature, the rate of energy consumption is proportional to the difference between the balance-point temperature and the external temperature:

$$\dot{q} = \frac{H(\tau)}{\eta}[t_{bal} - t_e(\tau)] \text{ when } t_e < t_{bal} \text{ and 0 otherwise} \tag{4}$$

where $\eta$ is the average efficiency of the heating system, $H(\tau)$ is the heat-loss coefficient (W/K/m$^2$) and $\tau$ is time (hr). With the assumption that $\eta$ and $t_{bal}$ are constant, the annual space heating demand can be written as an integral:

$$q_{yr} = \frac{1}{\eta}\int H(\tau)\,[t_{bal} - t_e(\tau)]^{+}\mathrm{d}\tau \tag{5}$$

where the plus sign above the bracket indicates that only positive values are included in the integral. As the space heating demand due to ventilation heat losses only is considered here, the heat-loss coefficient is given by:

$$H(\tau) = \rho c_p V \times \mathrm{ACH}(\tau) \tag{6}$$

where $\rho$ is the density of air (kg/m$^3$) at atmospheric pressure and a temperature of 20°C, $c_p$ is the specific heat capacity of air (J/kg/K), at constant pressure, and $V$ and ACH$(\tau)$ are the volume (m$^3$) and the ACH (/hr) of the conditioned part of the building envelope, respectively. These formulae are used to calculate the annual space heating demand due to ventilation losses in each archetype/permeability combination, assuming an average UK heating efficiency of 77% [1].

Piecewise cubic-hermite interpolation is used to estimate the annual space heating demand due to ventilation losses at $\mathrm{ACH}_{yr,ref}$ in the flat and house, and then energy savings compared to the reference dwellings are calculated.

# 3 Results

The modelled annual average air change rates, pollutant concentrations, risk of mould growth in the living room during the winter months, energy savings and health impacts compared to the reference dwellings for the flats and houses of all the modelled permeabilities are shown here. The results of the two multi-objective optimization approaches are then described.

## 3.1 Air change rates

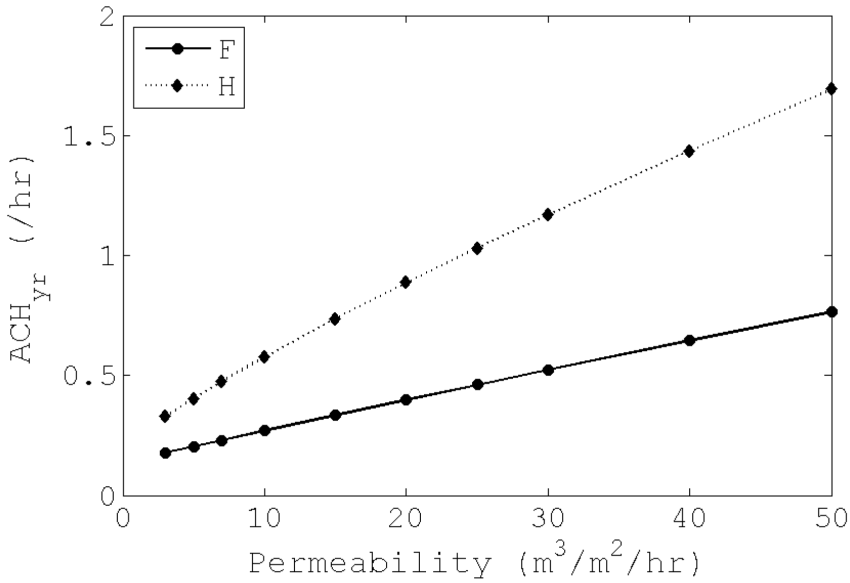
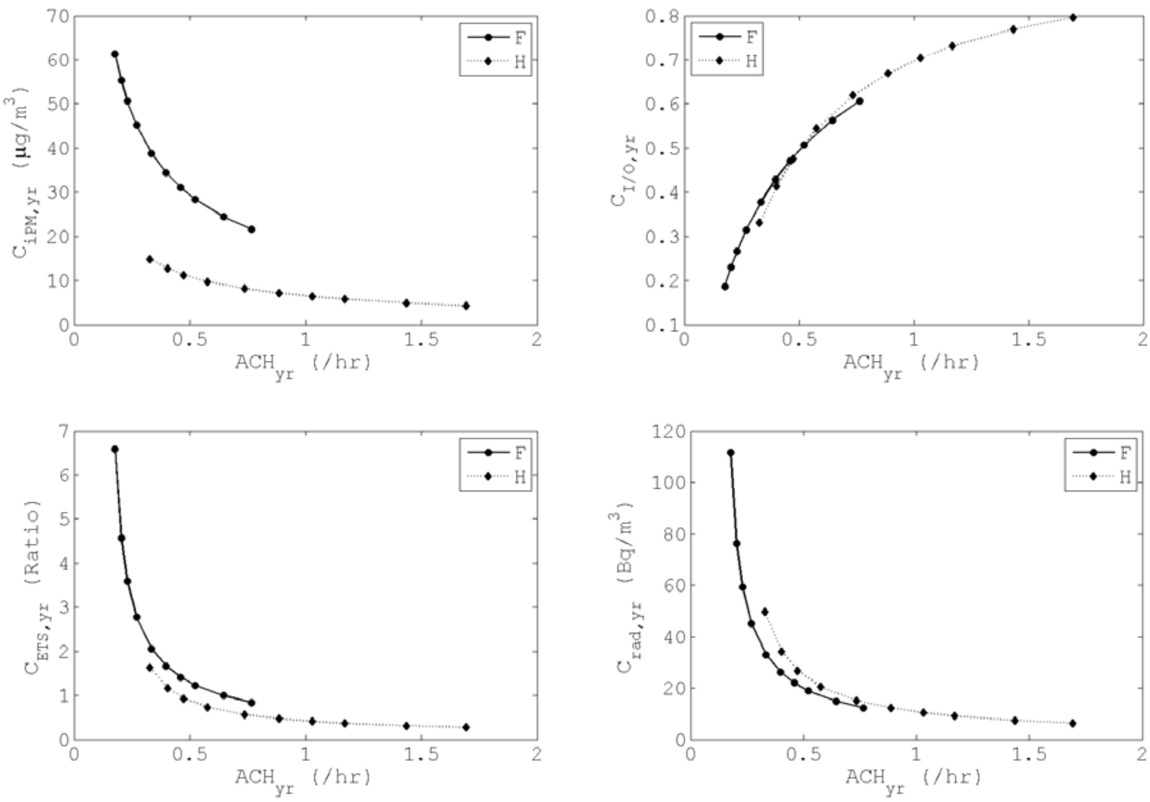



**Figure 1: Relation between annual average air change rate of the building envelope and permeability for a naturally-ventilated flat (F) and house (H).**

Figure 1 shows the relation between $ACH_{yr}$ for each archetype and the assumed permeability of the exposed façades. As expected, $ACH_{yr}$ is higher in the house as all façades are exposed to the external environment, while in the flat only two façades are exposed. In addition, the lower overall height of the flat results in a reduced stack effect. Both relations of $ACH_{yr}$ with permeability are approximately linear, but the relation for the house is steeper. The gradient of this relation should be approximately proportional to the ratio of the exposed surface area to the volume of the conditioned part of the building envelope. The flat has an exposed surface area of 36m$^2$ and volume 108m$^3$ giving a ratio of 0.33m$^2$/m$^3$. The house has an exposed surface area of 230.4m$^2$ and volume 230.4m$^3$ giving a ratio of 1m$^2$/m$^3$. Therefore the relation for the house should be approximately three times steeper (assuming similar operating schedules), and calculating the ratio of the gradients of the relations gives a value of 2.4, which is comparable.

## 3.2 Indoor exposures

Figure 2 shows the variation of $C_{\mathrm{iPM,yr}}$, $C_{\mathrm{I/O,yr}}$ scaled $C_{\mathrm{ETS,yr}}$, weighted $C_{\mathrm{rad,yr}}$, $\mathrm{MSI}_{\%>1}$ and $\mathrm{SIT}_5$ with $\mathrm{ACH}_{\mathrm{yr}}$. $C_{\mathrm{ETS,yr}}$, weighted $C_{\mathrm{rad,yr}}$, $C_{\mathrm{iPM,yr}}$, and $\mathrm{MSI}_{\%>1}$ all decrease as the dwelling becomes more permeable, both in the case of the flat and house. $C_{\mathrm{I/O,yr}}$ increases as the air change rate increases as a greater proportion of external $PM_{2.5}$ is able to infiltrate the dwelling from the outdoor air. $\mathrm{SIT}_5$ decreases as the air change rate increases, increasing the exposure of occupants to cold temperatures in the winter. The relationships between $C_{\mathrm{ETS,yr}}$, weighted $C_{\mathrm{rad,yr}}$, $C_{\mathrm{iPM,yr}}$ and $C_{\mathrm{I/O,yr}}$ and $\mathrm{ACH}_{\mathrm{yr}}$ are almost independent of dwelling morphology, while relations with internal $PM_{2.5}$ and mould risk are morphology dependent. $\mathrm{SIT}_5$ only depends on permeability, but as there are different relations between permeability and $\mathrm{ACH}_{\mathrm{yr}}$ between the dwelling archetypes, this translates into differing relationships with $\mathrm{ACH}_{\mathrm{yr}}$.



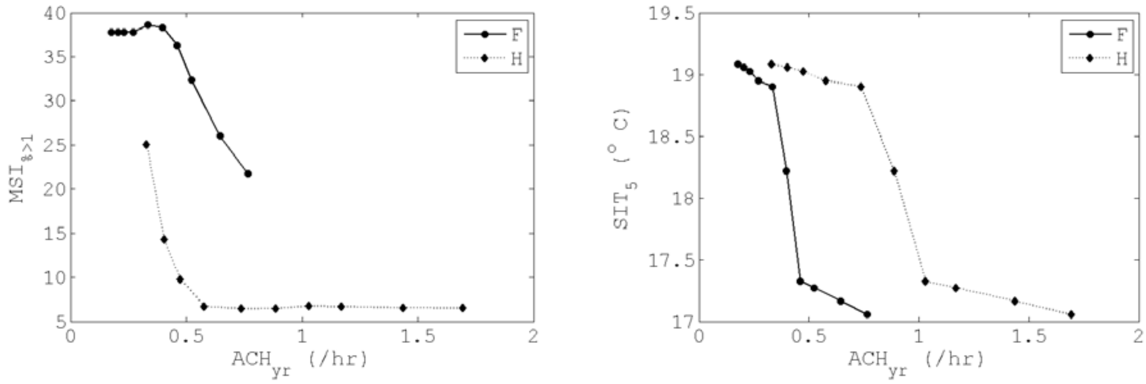



**Figure 2: Variation in concentration of internal $PM_{2.5}$, indoor/outdoor ratio of external $PM_{2.5}$, ETS, and radon, proportion of dwellings with a Mould Severity Index > 1, and winter indoor temperature (clockwise from top left) with annual average air change rate of the building envelope for a naturally-ventilated flat (F) and house (H).**

## 3.3 TRADE-OFFS BETWEEN HEALTH IMPACTS AND ENERGY SAVINGS

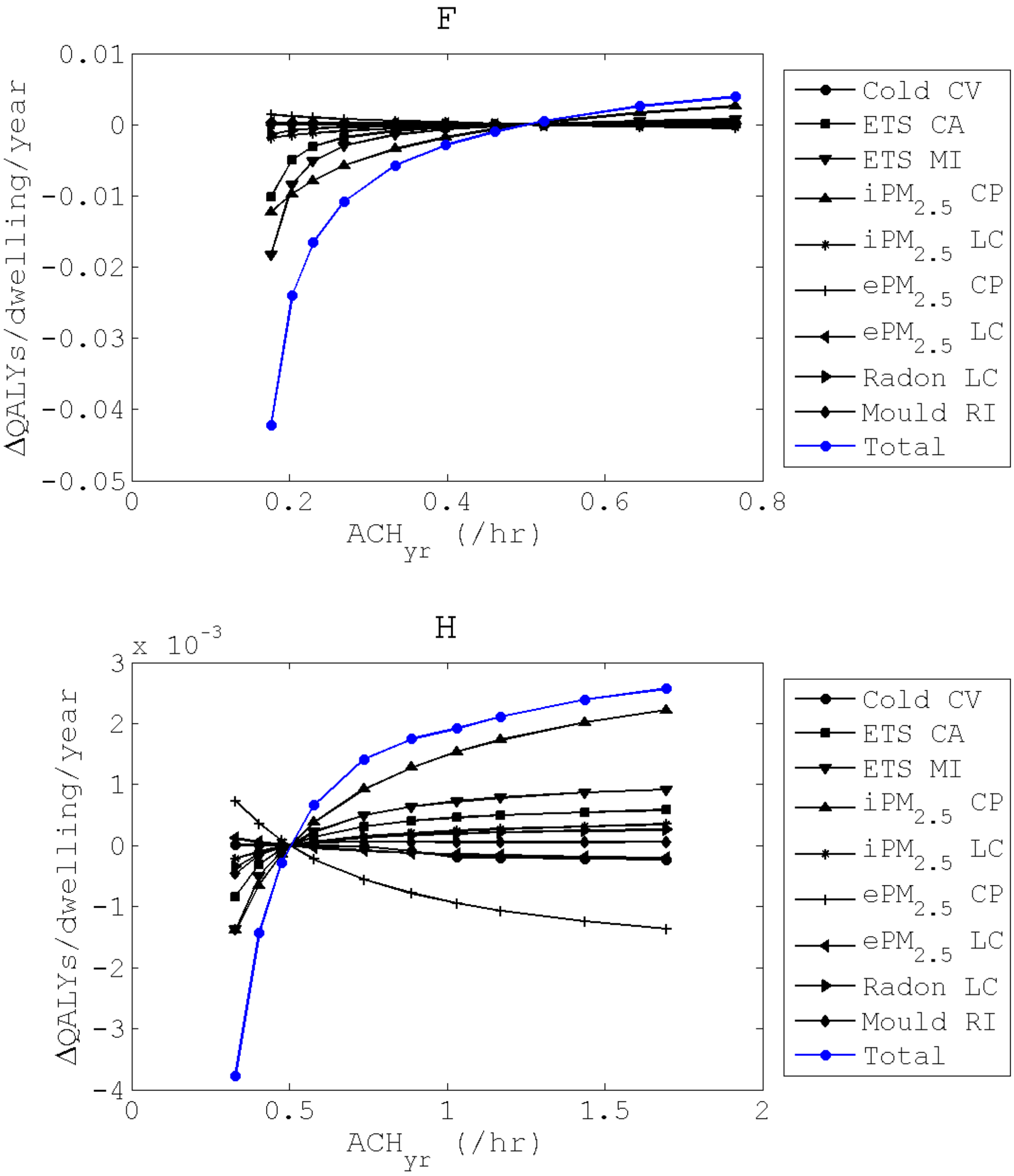



**Figure 3: Change in QALYS per dwelling per year against the annual average air change rate of the building envelope in flats (F) and houses (H). A positive change represents a positive health impact.**

Figure 3 shows the health impacts of exposure to the modelled pollutants and cold relative to exposures in the case of $ACH_{yr,ref}$, as a function of $ACH_{yr}$ of the building envelope.

The annual energy savings due to changes in ventilation heat losses are shown in Figure 4. The higher volume of the house building envelope compared to that of the flat and higher number of exposed façades results in a higher annual space heating demand in houses than in flats, even at the same $ACH_{yr}$.

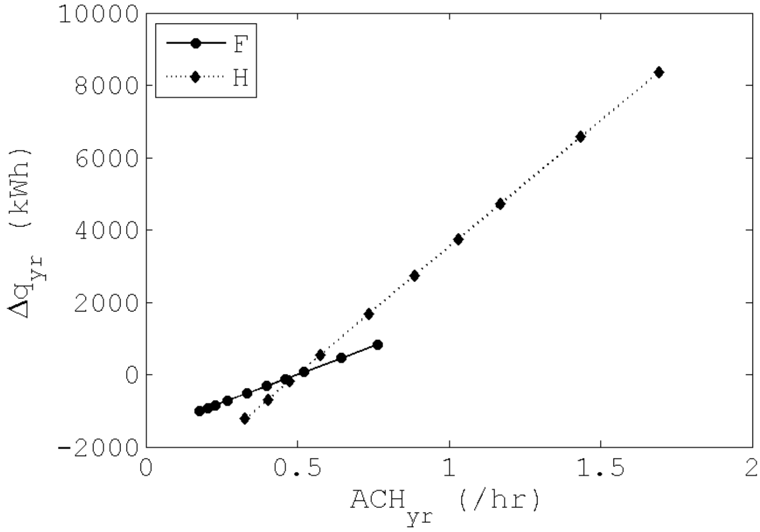



**Figure 4: Variation of annual energy savings with annual average air change rate of the building envelope.**

Figure 5 shows an example of the monetization approach for optimizing $ACH_{yr}$, for a energy price of 3 pence per kWh and a cost of £30,000 per QALY. For all relative costings explored, a true minimum in the total cost of energy use and health impacts in $ACH_{yr}$ could always be found in houses. As the price per QALY increases, the optimal $ACH_{yr}$ increases as health impacts dominate. As the price per kWh increases, the optimal $ACH_{yr}$ decreases as costs of space heating dominate. In the case of the flats however, true minimums are not as clearly defined in general, and therefore optimal $ACH_{yr}$ are towards the higher end of those explored in the CONTAM modelling. The variation of the optimal $ACH_{yr}$ with the cost per kWh is shown in the left plot of Figure 6. Optimal $ACH_{yr}$ for houses lies in the range 0.3-0.6/hr, depending on the relative costing between energy use and health impacts. Optimal $ACH_{yr}$ in flats is at least 0.6/hr, and could be much higher.

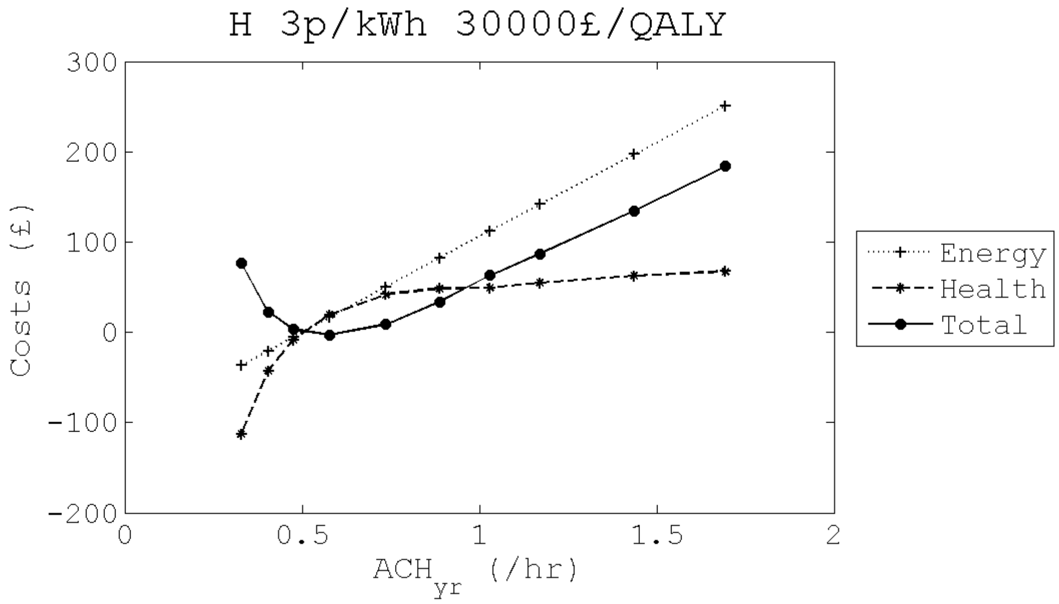



**Figure 5: Annual energy savings (energy), annual savings due to positive health impacts (health), and combined costs (total) against annual average air change rate assuming an average energy price of 3p/kWh and £30,000 per QALY in a house archetype.**

The results of the generalized multi-objective optimization approach are given in the right plot of Figure 6, which aims to allow a more flexible approach for weighting the performance criteria. The weight on the normalized annual average space heating demand is varied between 0 (representing annual health impacts only) and 1 (representing annual average space heating demand only). Considering energy savings only demands for no ventilation heat losses, while considering health impacts only results in an optimal $ACH_{yr}$ of around >0.8/hr, i.e. the maximum ventilation rates probed by our models. Assuming equal weighting between energy use and health impacts results in an optimal $ACH_{yr}$ of 0.8/hr in flats and 0.4/hr in houses. In both optimization approaches, the optimal $ACH_{yr}$ is higher in flats than in houses.

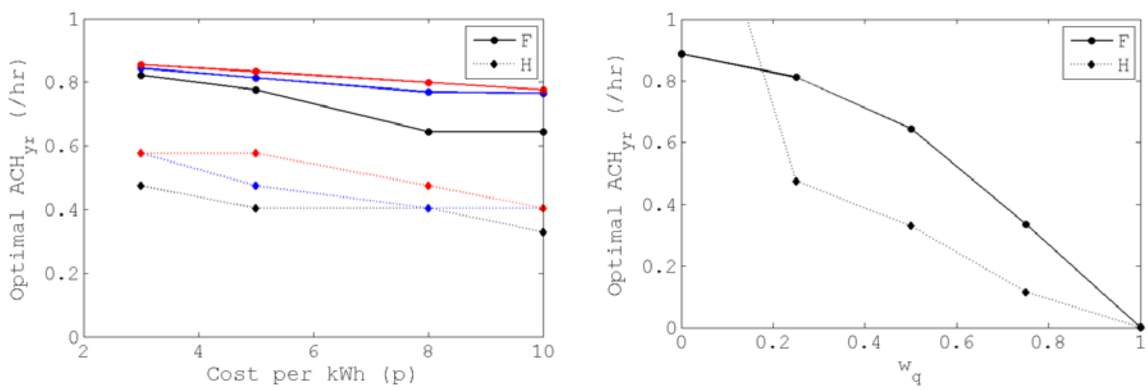


**Figure 6: Optimal annual average air change rate against weight given to annual energy savings using a monetization approach (left plot) and generalized multi-objective optimization approach (right plot). The different colours in the left plot correspond to assumptions of £20,000/QALY (black), £30,000/QALY (blue), and £40,000/QALY (red).**

# 4 Discussion

Here we discuss whether the models show a dependence of indoor environmental air quality and optimal ventilation rates on built form and the sensitivities of the optimal ventilation rates to the methods used and assumptions made in the calculations of energy savings and health impacts. We also initiate a preliminary discussion comparing the optimal ventilation rates determined in this work to recommended values in the UK building regulations.

## 4.1 Dependence of indoor environmental air quality on built form

The analysis of the indoor environmental quality in the case-study dwellings show that the relationships between $C_{\mathrm{ETS,yr}}$, weighted $C_{\mathrm{rad,yr}}$, $C_{\mathrm{ePM,yr}}$ and $C_{\mathrm{I/O,yr}}$ and $\mathrm{ACH_{yr}}$ are almost independent of dwelling morphology, while relations with internal $PM_{2.5}$ and mould risk are morphology dependent. The concentrations of the pollutants should correlate with the average ACH over the time they are being produced. Since radon and external sources of $PM_{2.5}$ are continuously present in all zones, their concentration would correlate only with the average ACH. Since the permeability of the dwelling is the main contribution to this, given the same weather conditions, then these pollutants are approximately independent of built form. Indoor sources of $PM_{2.5}$ and moisture however are produced during a time at which the ACH is increased temporarily as the windows are assumed to be open and in specific zones. Therefore the ACH during that time in that zone is more important than an average ACH. Since the window opening schedules are assumed to be the same in both dwelling types, the ACH in that zone and time would be a function of the dimensions of the room and the size of the window. Therefore these pollutants in the settings described here show a dependence on built form. In reality however, differing window opening schedules between dwellings could affect these observations.

## 4.2 Does optimal ventilation rate depend on built form?

The application of the multi-objective optimization methods described here to the case-study flat and house both imply the flats modelled may require a higher average air change rate. In the monetization approach and the generalized multi-objective optimization approach assuming equal weighting between health impacts and energy savings, the optimal ventilation rate is found to be 0.4/hr in the house and 0.8/hr in the flat, or equivalently ventilation rates of 0.3 l/s/m$^2$ in the house and 0.5 l/s/m$^2$ in the flat. These results suggest that ventilation rates recommended by many European countries and ADF of the UK Building Regulations [12] appear adequate in the detached house modelled here but not the flat. The discussion above regarding the differences between the dwelling types in the concentrations of internal sources of $PM_{2.5}$ and moisture showed that they are in particular attributable to smaller zones where they are being produced and smaller windows. Therefore it's not built form in general, it's in particular the size of the zones and windows in relation to each other. A simple solution could then be that in smaller kitchens/bathrooms, and those with small windows, one should open the windows for longer. These observations may be sensitive to several assumptions made in the various calculations in mind. These will be discussed in more detail below.

### *4.2.1 Uncertainties in calculation of energy savings*

The calculation of space heating demand due to ventilation heat losses is sensitive to the air change rate, assumed balance-point temperature, and assumed heating system efficiency.

A significant uncertainty in the calculation of the air change rate lies in assumptions made about the window opening schedules. The additional air change rates contributed by windows is proportional to the pressure difference between inside and outside and therefore is related to the base air change rate offered by the permeability of the walls. Opening the windows for longer would result in an overall higher air change rate until pressures inside and outside are equalized. Opening them for less time would result in an overall lower air change rate. The difference would be preferentially higher in dwellings with lower permeabilities, i.e. if all dwellings had the same window opening schedules but they were opened for longer, lower permeability dwellings would have an increase in air change rate that is greater than for higher permeability dwellings. Therefore ventilation heat losses differences between higher permeability dwellings and lower permeability dwellings would be lower and the energy saving associated with having a lower permeability dwelling would be lower. Pollutant concentrations would however also be lower and therefore the overall difference in the optimal ventilation rates may not be so different.

The balance-point temperature assumes an indoor design temperature of 18°C and internal gains of 2.5°C. Internal gains would however vary in reality with the size of the dwellings (e.g. number of electrical items could vary), occupant behaviour, and rate of heat loss from the dwelling. Therefore in the dwellings with higher permeabilities and higher rates of heat loss, lower internal gains would be expected and therefore an underestimate of the associated space heating demand. Therefore energy savings for dwellings with higher permeabilities may be overestimated and the optimal ventilation rate therefore may be an overestimate. In the case where internal gains are different from 2.5°C but the same between all dwellings, energy savings will change by a constant ratio and therefore affect the results of the monetization approach but not the generalized multi-objective optimization approach. In the monetization approach, the change will be greatest for the case in which QALYs cost £20,000/QALY and energy costs 10 pence/kWh, as the energy savings contribute most in this scenario to the total cost. In the generalized multi-objective optimization approach, the objective function is scaled by the maximum and therefore if the energy savings are scaled equally, the results will not change.

Finally, the UK average value for the heating system efficiency has been used. A lower heating system efficiency scales the energy savings up, and a higher heating system efficiency scales the energy savings down, and therefore it's value can potentially impact the optimal ventilation rates derived in the monetization approach but not in the generalized multi-objective optimization approach, unless the heating system efficiency is correlated with the permeability of the dwelling.

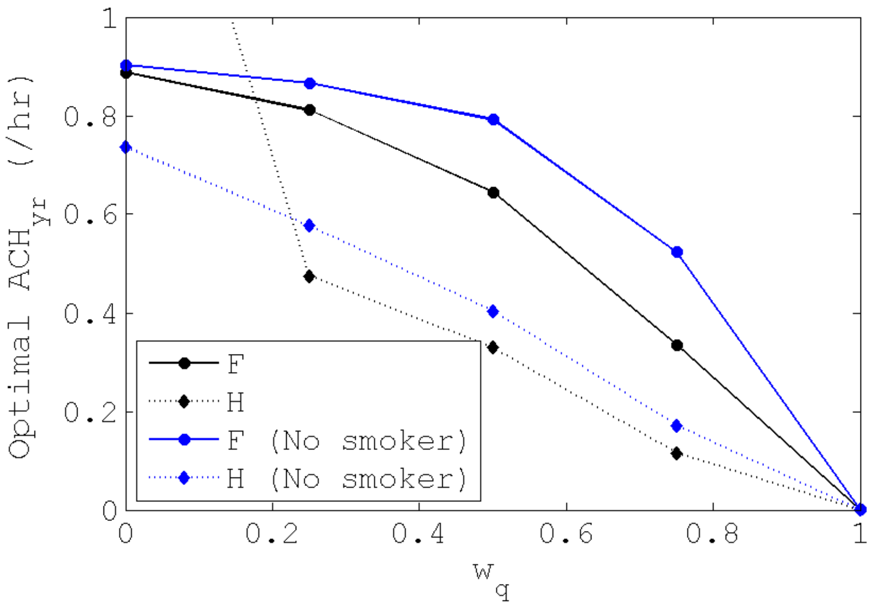



**Figure 7: Optimal annual average air change rate against weight given to annual space heating demand using a monetization approach (left plot) and multi-objective optimization approach. Blue shows the results for non-smoking results and black for smoking households.**

### *4.2.2 UNCERTAINTIES IN THE CALCULATION OF HEALTH IMPACTS*

The calculation of health impacts is sensitive to the number of pollutants considered, assumptions about their production and deposition, and dwelling occupancy.

The application of the multi-objective optimization in this work assumes that the dwellings have a smoker. In reality, the English Housing Survey [35] suggests that only 25% of households have at least one smoker. Therefore we repeat the optimization with no smoker. In the case of the monetization approach, no smoking results in less of a benefit from higher ventilation rates and therefore the optimal ventilation rates are lower. In the generalized multi-objective optimization approach however, optimal ventilation rates are in general *higher* (Figure 7) for non-smoking households with the same weight on energy savings, because health impacts contribution at lower ventilation rates compared to the reference dwelling are less extreme than before. Therefore the gradient of the composite objective function is gentler and the minimum occurs at a higher ventilation rate.

Assumptions about production rates of radon, moisture, ETS, and $PM_{2.5}$ all affect concentrations and the total subsequent health impacts and additionally in a permeability dependent way and would therefore impact on the results of both methods of multi-objective optimization.

A single average UK occupancy of 2.4 has been assumed. Although we would not expect a dependence with permeability, we would perhaps with dwelling type, i.e. flats may have a lower occupancy than houses. In this case, the results of the monetization approach would point towards more similar optimal ventilation rates between the dwelling types. However, as the occupancy is unlikely to change with permeability, there will be no change in the results of the generalized multi-objective optimization approach.

# 5 CONCLUSIONS AND FURTHER WORK

The work in this paper presents monetization and generalized multi-objective optimization approaches for determining the optimal ventilation rates in residential dwellings by considering both energy savings and health impacts compared to reference dwellings with $ACH_{yr}$ of 0.5/hr. Using a monetization approach for multi-objective optimization can be useful if costs associated with the various objective functions are comparable, as in the case of the typical UK house. Generalized multi-objective optimization has also been shown to be robust against any scaling in the health impacts and energy savings, and therefore is less dependent on assumptions made in the calculations such as heating system efficiency, toxicity of pollutants, and dwelling occupancy. It is however sensitive to assumptions affect health impacts and energy savings in a way directly correlated with permeability such as pollutant production rates, or balance-point temperatures. It should also be noted that it is important in both cases to consider the whole set of important pollutants as in the monetization approach it affects the total health impacts and in the generalized multi-objective optimization approach the concentration of each changes differently with ventilation rate, and therefore affects the gradient of the objective function.

A preliminary application of the methods to a typical UK flat and detached produced the following observations:

- Concentrations of external $PM_{2.5}$, ETS, and radon may be independent of built form.
- The optimal ventilation rate may vary according to the built form. The analysis in this paper suggests a far greater value in the flat compared to the detached house. Both the monetization approach and generalized multi-objective optimization approach in which health impacts and energy savings are equally weighted suggest and optimal $ACH_{yr}$ of 0.4/hr for the house, and 0.8/hr for the flat. This is equivalent to ventilation rates of 0.3 $l/s/m^2$ for the house and 0.5 $l/s/m^2$ for the flat.

Future work will investigate optimal ventilation rates for a representative set of UK archetypes to further explore whether there is a dependence on building morphology. A more in-depth study will also be carried out on the influence of the toxicity of indoor $PM_{2.5}$ (less well established than outdoor $PM_{2.5}$) and time-lag effects of exposure to radon. There will also be further exploration of other multi-objective optimization methods such as genetic algorithms, which enable sets of Pareto optimal solutions to be obtained.

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